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Original research paper

AGROECOLOGICAL CONDITION AND FUNCTIONALITY OF WINDBREAK BELTS IN THE OVCHE POLE REGION

Jordancho Dimitriev[1,2*], Fidanka Trajkova[2], Ljupco Mihajlov[2]

[1]Faculty of Agriculture, Goce Delcev University, Krste Misirkov 10-A, 2000 Stip, Republic of North Macedonia
[2]Ministry of Agriculture, Forestry and Water Economy, Inspectorate for Forestry and Hunting, Republic of North Macedonia

**Corresponding author: jordanco.209148@student.ugd.edu.mk*

Abstract

Windbreak forest belts in the Ovce Pole region were established approximately 65 years ago, aiming to protect agricultural land, reducing wind erosion, and improving the local microclimate. Due to their advanced age, insufficient maintenance, agricultural intensification, anthropogenic pressures, and the impacts of climate change, many of these belts have experienced a decline in their protective and ecological functions. The aim of this study was to assess the current agroecological condition, structure, and functionality of selected windbreak belts in the Ovce Pole region, with particular focus on the Municipality of Sveti Nikole. The research methodology combined a review of relevant literature, field observations, GPS-based georeferencing, morphometric measurements and dendrological analysis of vegetation condition. The assessed indicators included belt continuity, species composition, the proportion of cut and dry trees, the occurrence of dieback, grass cover, trampled vegetation, and the presence of leaf necrosis and chlorosis. The results from this research show that a considerable proportion of the investigated belts is degraded, fragmented, or affected by illegal cutting, natural senescence, drought stress, and inadequate management. The study confirms the importance of windbreak belts for agroecosystem stability and highlights the need for systematic restoration, strengthened institutional protection, and long-term maintenance.

Key words: *wind erosion, microclimate, agroecosystems, soil protection, sustainable agriculture.*

INTRODUCTION

Ovce Pole is among the driest and windiest regions in the Republic of North Macedonia, where agricultural production is exposed to multiple environmental risks. Strong winds, high temperatures, and low relative humidity contribute to soil degradation, increased evaporation, and reduced crop productivity (Onchevski et al., 2022). Under such conditions, windbreak belts play a crucial role in protecting arable land by mitigating the adverse effects of wind and improving conditions for crop growth.

Protective forest belts are purposefully established woody formations on agricultural land designed to prevent aeolian erosion and wind-induced soil degradation, enhance soil moisture retention, and contribute to the regulation of the local water regime. In addition, they improve soil fertility and microclimatic conditions. In predominantly open agricultural landscapes, such belts increase woody vegetation cover and support biodiversity conservation. Their ecological and economic importance is particularly pronounced in arid and deforested regions.

Windbreak belts are recognized as an important component of agricultural systems, contributing to crop production, environmental protection, and the reduction of external inputs (Brandle et al., 2004). Tree-based windbreaks provide multiple ecosystem services in rural landscapes, including microclimate regulation, soil protection, biodiversity support, and overall

landscape functionality (Weninger et al., 2021). When properly designed and spatially arranged, windbreak belts effectively reduce wind velocity and minimize soil loss across agricultural areas (FAO, 2020). Recent studies also confirm that windbreaks and shelterbelts contribute to ecosystem protection, climate change mitigation, and improved agricultural productivity (Enescu et al., 2025).

Afforestation activities in the Ovce Pole region for agricultural land protection and improvement of the local microclimate began in 1950 and were completed by 1956. During this period, windbreak belts were established over an area of approximately 555.66 ha, forming a rectangular network across agricultural parcels (Onchevski et al., 2022). The tree species used in their establishment are characterized by a relatively limited functional lifespan of approximately 30 years, suggesting that many existing belts have exceeded their optimal vitality period. The predominant species included black locust (*Robinia pseudoacacia*), honey locust (*Gleditsia triacanthos*), almond (*Prunus dulcis*), Japanese pagoda tree (*Styphnolobium japonicum*), ash (*Fraxinus spp.*), and other species adapted to local environmental conditions.

A considerable portion of the original windbreak system has been degraded or lost due to land-use changes and illegal cutting, resulting in reduced effectiveness in wind-speed mitigation (Onchevski et al., 2022). The management, protection, and utilization of forests, including felling, afforestation, and protective measures, are regulated by the Law on Forests (Official Gazette of the Republic of Macedonia, No. 64/09, with subsequent amendments).

The aim of this study is to assess the background and the current ecological condition of windbreak belts in the Ovce Pole region through an analysis of their establishment and management, as well as through the evaluation of selected ecological and structural indicators. These include the proportion of cut, dry, and dieback-affected trees, the presence of grass cover, the occurrence and intensity of leaf necrosis and chlorosis, and the extent of degraded or destroyed vegetation within the belts.

The research aim is to identify the main environmental and management factors affecting windbreak functionality, determine existing structural and management deficiencies, and highlight key challenges to their sustainability. Based on the findings, measures for restoration, protection, and long-term maintenance are proposed.

MATERIAL AND METHODS

Study area

Field research was conducted in selected windbreak belts within the Ovce Pole region, in the Municipality of Sveti Nikole, Republic of North Macedonia. According to recorded geographic coordinates, the study area is located between 41°52′27″ and 41°58′44″ N latitude and 21°27′18″ and 21°33′21″ E longitude (Greenwich meridian) (Figure 1).

Geographical coordinates were additionally recorded in the UTM coordinate system for spatial analysis of the study sites.

Point 1: Y = 7,575,099.99; X = 4,641,127.88
Point 2: Y = 7,574,493.48; X = 4,640,769.66
Point 3: Y = 7,574,654.78; X = 4,640,491.74
Point 4: Y = 7,575,373.47; X = 4,640,938.20



Figure 1. Windbreak belts in the study area (photo: Jordancho Dimitriev).

Research methodology

A combined theoretical, field and analytical approachs were applied to collect primary data through literature review, direct field observations and *in situ* measurements.

In order to provide an adequate scientific foundation for the interpretation of the field findings, the article includes a theoretical analysis of the structure, functioning, and agroecological impact of windbreak belts. The theoretical section is built upon a systematic review of relevant domestic and international scientific literature, including monographs, peer-reviewed research articles, and technical reports from international institutions. This approach was applied to place the empirical results obtained in the field within a broader context, enabling their comparison with international experience and standards, and providing a scientific framework for formulating recommendations regarding the restoration and management of windbreak belt systems in the Ovche Pole region.

Field research was conducted at previously identified sampling locations within the study area. The field procedures included precise georeferencing of the windbreak belts using GPS devices, measurement of morphometric characteristics along predefined transects, dendrological analysis of species composition, assessment of density and continuity, and documentation of degradation processes.

Morphometric measurements showed that the distance between Point 1 and Point 2 was 0.705 km, while the distance between Point 3 and Point 4 was 0.833 km. The width between Point 2 and Point 3 was 262 m, whereas the effective width of the planted strip was approximately 10 m. Vegetation height ranged from 6 to 8 m. In other windbreak belts within the study area, lengths ranged from 0.1 km to 3.0 km, belt widths ranged from 100 m to 300 m, and vegetation height ranged from 8 to 10 m.

The identified tree species included black locust (*Robinia pseudoacacia*), honey locust (*Gleditsia triacanthos*), almond (*Prunus dulcis*), sophora (*Styphnolobium japonicum*), European ash (*Fraxinus excelsior*) and other associated species. The analysed belts were classified as permeable, semi-permeable and non-permeable according to the openness of their cross-sectional structure. According to their orientation relative to the prevailing winds, they were classified as main and secondary belts.

Photographic records and field notes were collected to support the analysis. The study also used comparative observations of agricultural plots with and without windbreak belts. Key parameters considered in the evaluation included wind speed, soil moisture, air temperature and crop yield. Structured interviews with local farmers were also used to obtain practical insights into the perceived effects and benefits of windbreak belts.

RESULTS AND DISCUSION

Theoretical analysis

Windbreaks belts: concept and function

The windbreak belt is a natural or artificial barrier that reduces the challenging winds through creation leeward. Its main function is to reduce wind speed. Windbreaks belts need to be at least 760 cm high to have significant effect. The practice includes intensive management with trees, shrubs and/ or grass, where the plants are planted under right angle in relation to the prevailing winds (Brandle et al., 2004; University of Missouri, 2021).

The forest belt significantly reduces wind speed in the zone which stretches up to 10–15 times bigger than his height, on the side opposite of wind and 3-5 times on the side turned towards wind (McNaughton, 1988). The degree of protection depends primarily on the density, height, and cross-sectional shape of the windbreak belt. The streamlined profile with gradual transition is more efficient than a vertical one, because the wind more easily passes over the uniformly tapered profile of the shelterbelt (Shaw, 1988). In addition, windbreak systems influence soil erosion, snow retention, moisture, biodiversity, and the productivity of agricultural crops (Caborn, 1965; FAO, 2014; Trajkova et al., 2021).

Mode of operation

The functioning and efficiency of the windbreak belt are determined by seven structural elements: (1) Height - it determines protective zone in the direction of the wind and it is a basic parameter for calculating the protective coverage; (2) Density - the ratio of

solid part towards the total barrier surface, crucial for the wind regime; (3) Orientation - ideally under right angle of the prevailing wind, with deviation no greater than 45°; (4) Length - should exceeds the height by 10:1 to avoid the effect of a side wind; (5) Width - controls density and protective benefits for wildlife; (6) Continuity - each emptiness or interruption concentrates and strengthens the wind in the zone behind the interruption; (7) Shape of a cross section - effect on permeability and wind speed profile (Table 1).

The thick component (60–80%) provides maximum wind reduction, but creates short protective shadow. Moderate thick component (40–60%) gives a smaller direct reduction, but provides a longer and more even protective zone. Component below 40% is effective for optimal snow distribution and regulation of microclimate conditions (Shaw, 1988; University of Missouri, 2021). Research by Souza et al. (2013) shows that the optimal average permeability for maximum leeward length is ~35%.

Table 1. Wind speed reduction in the leeward of the windbreak belts with different density (Source: University of Missouri, 2021).

Belt type	Belt density	Wind speed	5 m	10 m	30 m	Conclusion
Leafy greens	25–35%	10 m/s	50%	65%	100%	Weak protection; at bigger distance the wind is returned with the initial speed
Conifers	40–60%	10 m/s	30%	50%	95%	Better protection; stable wind reduction
Multi-row belt	25–35%	10 m/s	25%	35%	95%	Most effective protection; maximum wind reduction
Solid fence	25–35%	10 m/s	25%	70%	100%	Very quickly reduction behind the fence, but fast return speed and risk of turbulence

Types of windbreak belts

According to their purpose, windbreaks belts can be: for households and farms (protection, shade, aesthetics and reduction of energy consumption), for fields (protection of crops and soil from aeolian erosion, moisture and snow retention, for livestock (shelter, stress reduction), live fences for snow (retention or snow drifts), and wind shields wild animals (ecological corridors). According to composition, they can be composed by trees and shrubs (deciduous or conifers), fences (snow, mobile) and earthen berms (Barbeau et al., 2018; FAO, 2014). In agroecological context, especially significant are field windbreak belts - woodland stripes composed mostly deciduous trees, permeable to medium-thick by their structure, oriented vertically on the dominant winds and integrated into the agricultural landscape mosaic. This class of windbreak belt systems is subject to this research.

Design of windbreaks belts

There are four basic Design types: (1) Single row - for protection of fields and orchards, with limited value for the wildlife and relatively low protective efficiency for strong winds; (2) Double-row - for protection of larger field and farm surfaces, with certain benefits for wildlife; (3) Three-row - for larger agricultural areas and pastures, with bigger biodiversity value and better structural stability; (4) Four and multi-row - for farms and pastures, with high value for the wildlife and maximum protective efficiency, but they take significant land area.

During the windbreak belts design the specific climatic and soil conditions shall be taken into account. For arid- and semiarid climatic conditions similar to Ovche Pole, recommends a moderately thick structure with ~60% coverage, planted with indigenous or well adapted species in 3–5 rows, with specific mix of woody and shrubby plants species for optimizing the permeability profile (JICA, 2023a).

Agrotechnical influence on agriculture

Windbreak belts provide numerous direct benefits for agriculture: soil erosion control, improved moisture retention, reduction of evaporation and transpiration of crops, protection of agricultural crops and livestock from physical damage. The key advantage is their potential for reducing the energy consumption - land circumambulated with trees requires no intensive cultivation and application of pesticides and fertilizers, with that reducing the nitrogen oxide and carbon dioxide emissions (Brandle et al., 1992; Little et al., 2008; Mihajlov et al., 2010; Mihajlov, 2023).

Windbreak belts scenarios show that they can reduce energy consumption for climatization and heating by 10–25% (Ballesteros- Possu et al., 2017). The highest yield increases are noted in the "silent zone", approximately 3–10 times greater than the height of the protective barrier (Norton, 1988; Baldwin, 1988; Eastham et al., 1990). Research by Zhen et al. (2016) show that the zones protected with woodland stripes achieve on average 10–20% higher wheat and corn yields in dry years. Rivest & Vezina (2015) determined that corn yields in protected areas zones were up to 17% higher.

Windbreak belts affect the movement of pests, pollen and pathogens. Good designed windbreak belts can increase biodiversity, introducing natural predators which help in pest control and reduce the need for pesticides. However, in the immediate vicinity of the trees a shading, competition for nutrients and increased humidity, with potentially localized reduction yield can occur (Qiao et al., 2016; Szigeti et al., 2020). The recommendations indicate that there is need for 2-4 m wide buffer zones between the woodland stripe and the agriculture plot to minimize the competition.

Agroecological influence on the environment
Impact on the microclimate

Windbreak belts significantly reduce wind speed, causing measurable changes in the microclimate of the protected area (Geiger et al., 2009). The daily air temperatures near average thick windbreak belts can be 1–3°C higher, and the temperature increase provides farmers possibility for earlier marketable products. The night temperatures in the ground layer usually are higher by 1–2°C, reducing the risk of radiation ice (Brandle et al., 2004; McNaughton, 1988).

The soil temperature in protected areas is usually a little higher, with exception of zones in direct shadow. The thick windbreak belts (> 60% density) concentrate the snowy drifts in short and deep shape on the side opposite the wind, while porous (~35%) provide longer and shallower snow distribution, which protects winter crops and complements soil moisture reserves in spring (Shaw, 1988). The evaporation in protected zones is reduced by 20–30% due to the reduced wind speed, while the air humidity is higher, reducing the risk of drought and radiation ice (Brandle et al., 2004; Geiger et al., 2009). Potashkina & Koshelev (2022) established that windbreak forest stripes contribute to better water balance and reduce soil moisture deficit of up to 25% in dry periods.

Impact on biodiversity

The windbreak belts have positive role on agricultural biodiversity landscapes because they serve as basic habitats and ecological safe corridors for safe wild animals' movement (Yahner, 1983; Haas, 1995; Harvey et al., 2008; Peters & Nibbelink, 2011). Tree, seed and bird diversity is higher in windbreak belts as compared to the surrounding arable fields (Harvey, 2000; Montagnini & Jordan, 2005). The structural complexity of windbreak belts additionally increases the availability of resources for animals – the multifaceted plantations offer vegetation, food (berries, fruits), shelter and nesting sites.

The presence of windbreak belts in the agricultural landscape is connected with increasing populations of pollinating insects, natural enemies of pests and singing birds (Burel, 1996; Burel & Baudry, 1990; Oreszczyn & Lane, 2000). Pascual-Hortal & Saura (2006) confirmed that the woodland stripes act as "stepping stone" habitats which connect the bigger forest arrays in fragmented agricultural landscape mosaics. Taking in consideration all above, the windbreak systems are considered as key element in green infrastructure for agroecological planning.

Carbon balance and climate effects

Besides the direct agroecological effects, windbreak systems contribute to mitigation of climate change through carbon sequestration. Kort & Turnock (1998) estimate that mature windbreak system sequesters average 5–25 t CO_2/ha/year, depending on the species composition, their age and conditions. Ballesteros-Possu et al. (2017) confirm that windbreak systems represent profitable mechanism for reduction of carbon footprint on agricultural farms. Furthermore, with reduction of soil erosion, they help to preserve the organic carbon in the soil, additionally contributing towards the balance of greenhouse gas (Brandle et al., 1992).

Empirical analysis

Characteristics of windbreak belts in Ovche Pole region

Chronological establishment

The systematic establishment of windbreak belts (field shelterbelts) in the Ovche Pole region started directly after the Second World War in 1946/47, when the Forestry Institute in Skopje carried out first experimental afforestation. By 1950, the General project was drawn up. In 1951, the initiative was accepted at the federal level and it became part of a wider federal program for agricultural improvement. In the period 1957-1959, it continued to be intensively spread (JICA, 2023a).

The period 1970–1990 represents the highpoint of development and functionality - windbreak belts have been regularly maintained by agricultural combines and public institutions, successfully reducing the wind speed and positively influencing the yields. The systematic care had included regular thinning, sanitary cuttings and replanting. After the transitional changes, from 1990 onwards, the windbreak belts maintenance significantly decreased, due to dissolution of agricultural combines, changes in ownership structure and reduction of institutional capacity. Part of windbreak belts were cut down, neglected or fragmented (FAO, 2014). The activities of the JICA Eco-DRR project (2017–2022) (JICA, 2023b) represent first organized international intervention for the restoration and promotion of windbreaks systems in the region.

Location and area

The Ovche Pole region is located in the east-central part of North Macedonia, with elevation difference 200–400 m above sea level. The center of the region is the city Sveti Nikole, and the region stretches between the rivers Bregalnica and Vardar. Initially, the windbreak belts covered ~600 hectares, with ~83 forest stripes. The width of the strips varies from 10 to 20 meters, the length from 0.5 to 15 km. They form rectangular network with agricultural plots ~1000 m long and ~250 m wide, following the main directions of the dominant NW and SE winds. Today, due to fragmentation and degradation, it is estimated that around half of the original surface is lost or damaged (Onchevski & Mihara, 2024).

Land ownership

The land ownership structure is heterogeneous. It encompasses public, private and mixed land ownership. Significant part was transferred to private ownership after restitution conducted in the 1990s. The research show that ~50% of windbreak belts are lost or degraded due to change in agricultural use, irresponsible privatization, absence of protective measures regulations and lack of financial maintenance mechanisms (Onchevski & Mihara, 2024).

The unclear proprietary status results with insufficient maintenance, illegal logging or conversion to agricultural land (Villanueva et al., 2020). The Law on Forests (Official Gazette of the Republic of Macedonia, No. 64/09, with subsequent amendments) includes protective state forests jurisdiction, but enforcement and inspection mechanisms are limited. Huang et al. (2006) and Villanueva et al. (2020) emphasize that insecurity of land rights is one of the key factors which demotivates the investment in long-term agroecological measures.

Natural conditions in the Ovche pole

The Ovche Pole valley is spacious plain with small high-altitude differences (200-400 m). The absence of natural compartments, the strong winds (maximum 8.5 m/s, mainly NW direction), dry and hot summer with low precipitation (~110 mm in vegetation period, average annual temperature 16.6°C) and the light soils (smolnica, rendzini, regosol, chernozem, alluvial) create high wind risk erosion. The limited forest cover (below 5% in the plain part of the valley) makes the establishment of windbreak systems agroecological necessity (Geografski institut, PMF - Skopje, 2015).

Climatological research show that the frequency of days with wind speed >5 m/s is

significant (35–50 days annually), when the wind blowing causes intensive dust and suspended particles which degrade agricultural crops in sensitive phenological phases (flowering, fruiting). The aeolian erosion in such a context can caused loss of 5–15 mm of upper humus layer per year on unprotected land, with direct and long-term consequences on soil fertility.

Field research results

The investigated windbreak belts in the Sveti Nikole area differed in species composition and structural characteristics (Table 2). According to the permeability, the windbreak belts from study area were classified as permeable, semi-permeable and non-permeable belts. The studied windbreak belts were classified as primary or secondary belts according to their orientation relative to prevailing winds. The primary belts were positioned perpendicular to the dominant winds, while the secondary belts were positioned perpendicular to the primary belts, i.e. generally parallel to the prevailing wind direction. The analysis showed that common ash (*Fraxinus excelsior*) was dominant in the permeable and semi-permeable windbreak belts, while field maple (*Acer campestre*) was dominant in the non-permeable belts. Permeable belts generally lacked a developed shrub layer, whereas semi-permeable belts showed the highest shrub diversity. In non-permeable belts, black elder (*Sambucus nigra*) and field maple (*Acer campestre*) regeneration formed the main undergrowth.

Table 2. Species composition and structural characteristics of field windbreak belts in research area in Ovche Pole.

Belt type	Direction / orientation	Dominant species	Secondary species	Occasional trees	Shrub layer
Permeable	Main belts	Common ash (*Fraxinus excelsior*)	Common oak (*Quercus robur*)	Small-leaved lime (*Tilia cordata*)	Not recorded
Permeable	Supplementary belts	Common ash (*Fraxinus excelsior*)	Not recorded	Not recorded	Not recorded
Semi-permeable	Main belts	Common ash (*Fraxinus excelsior*)	Common oak (*Quercus robur*)	Black locust, wild cherry, wild plum, wild pear (*Robinia pseudoacacia, Prunus avium, Prunus cerasifera, Pyrus pyraster*)	Rosehip, hazel, ash shrubs, field maple (*Rosa canina, Corylus avellana, Fraxinus ornus, Acer campestre*)
Semi-permeable	Supplementary belts	Common ash (*Fraxinus excelsior*)	Wild plum, wild pear (*Prunus cerasifera, Pyrus pyraster*)	Black elder (*Sambucus nigra*)	Black elder (*Sambucus nigra*)
Non-permeable	Main belts	Field maple (*Acer campestre*)	Eucalyptus / common oak (*Eucalyptus globulus, Quercus robur*)	Common oak (*Quercus robur*)	Black elder (*Sambucus nigra*) and field maple regeneration (*Acer campestre*)

The degradation indicator of windbreak belts in Ovche Pole region are presented in Table 3. The highest percentage of logged trees was recorded in the main permeable windbreak belts (33%), which constitutes an alarming value. No logged trees were found in the supplementary permeable belts. In the main and supplementary semi-permeable belts, the percentages were 5% and 3% respectively, while in the impermeable belts it was 8%. The causes of logging include physiological dieback, unauthorized cutting, disease, pest infestation, fire, and biological senescence.

The highest percentage of completely dead trees was recorded in the supplementary semi-permeable windbreak belts (15%), predominantly composed of common hornbeam (*Carpinus betulus*), attributed to its susceptibility to leaf diseases (*Apiognomonia spp.*) and interspecific competition with dominant tree species. In the main semi-permeable belts, 8% of trees were dead (*Fraxinus excelsior*), while it was 2% in both permeable belt types (*Fraxinus excelsior* and *Carpinus betulus*). The trees in the process of dieback were most prevalent in the main permeable windbreak belt (33%, *Fraxinus excelsior*) and in both the main and supplementary semi-permeable belts (15% each). This widespread dieback of *Fraxinus* spp. is consistent with the situation documented across Europe, where Hymenoscyphus fraxineus causes up to 90% mortality in affected ash populations (Kowalski, 2006; Pautasso et al., 2013).

In addition to natural tree mortality, numerous stumps from trees cut within the past five to ten years were identified. The causes of tree removal are likely multifactorial and include natural dieback, illegal logging, anthropogenic fire damage, pest and disease incidence, and senescence of planted trees.

Grass cover in windbreak belts varied among belt types. Bare patches were recorded in the impermeable belts, partial grass cover was present in the main permeable and semi-permeable belts, while dense couch grass (*Elymus repens*) was recorded in the secondary permeable and semi-permeable belts. Trampled grass vegetation accounted for approximately 10% in these secondary belts.

Table 3. Degradation indicators of windbreak belts in research area in Ovche pole.

Parameter	Permeable main belt	Permeable supplementary belt	Semi-permeable main belt	Semi-permeable supplementary belt	Impermeable main belt
Participation of logged trees	33%	-	5%	3%	8%
Participation of dead / dry trees and their species composition	-	2% Common ash (*Fraxinus excelsior*)	8% Common ash (*Fraxinus excelsior*)	15% Common hornbeam (*Carpinus betulus*)	2% Common hornbeam (*Carpinus betulus*)
Dieback trees and their species composition	33% Common ash (*Fraxinus excelsior*)	2% Common ash (*Fraxinus excelsior*)	15% Common ash (*Fraxinus excelsior*)	15% Common hornbeam (*Carpinus betulus*)	2% Common maple (*Acer pseudoplatanus*)
Grass cover in windbreak belts	Partially present	Couch grass (*Elymus repens*)	Lily (*Lilium sp.*) Nettles (*Urtica sp.*)	Couch grass (*Elymus repens*)	Bare patches
Participation of trampled grass vegetation	/	10%	/	10%	/

The manifestation of leaf necrosis and chlorosis represents one of the most frequently observed symptomatic deviations in the examined systems. Signs of necrosis and chlorosis occur as a result of airborne pollutants, soil toxins, low-temperature stress (frost), drought stress, pathogen infections, or pest attacks (Mazur et al., 2025). The highest incidence of necrosis was found in the supplementary semi-permeable windbreak belt, 40% in hornbeam (*Carpinus betulus*) and 35% in common maple (*Acer pseudoplatanus*), indicating severe physiological disturbances. In the supplementary permeable belt, 25% of ash trees (*Fraxinus excelsior*) were affected. Chlorosis was likewise most pronounced in the supplementary permeable belt (30% in ash) and in the main semi-permeable belt (60% in ash).

The high proportion of chlorotic leaves in the main semi-permeable belt (60% in ash) may indicate a deficiency of mineral nutrients, particularly iron, manganese, or magnesium, pH disturbances in the rhizosphere, or severe seasonal drought stress. This value is notably high compared to the norms described in the literature for healthy stands, where chlorosis typically affects less than 10% of foliage (Mazur et al., 2025). The overall pattern of necrosis and chlorosis distribution suggests that the supplementary belts are under greater physiological stress than the main belts, likely due to greater exposure to edge effects and more intense interspecific competition.

Table 4. Leaf necrosis and chlorosis occurrence and proportion of windbreak belt tree species in research area in Ovche Pole region.

Parameter	Permeable main belt	Permeable supplementary belt	Semi-permeable main belt	Semi-permeable supplementary belt	Impermeable main belt
Leaf necrosis (occurrence)	2% Common ash (*Fraxinus excelsior*)	25% Common ash (*Fraxinus excelsior*)	5% Common ash (*Fraxinus excelsior*)	40% European hornbeam (*Carpinus betulus*) 35% Common maple (*Acer pseudoplatanus*)	3% Common maple (*Acer pseudoplatanus*)
Leaf necrosis (proportion)	15% Norway maple (*Acer platanoides*) 2% Common ash (*Fraxinus excelsior*)	7% Common ash (*Fraxinus excelsior*)	8% Common ash (*Fraxinus excelsior*)	18% European hornbeam (*Carpinus betulus*) 25% Common maple (*Acer pseudoplatanus*)	4% Common maple (*Acer pseudoplatanus*)
Leaf chlorosis (occurrence)	7% Common ash (*Fraxinus excelsior*)	30% Common ash (*Fraxinus excelsior*)	5% Common ash (*Fraxinus excelsior*)	18% European hornbeam (*Carpinus betulus*) 25% Common maple (*Acer pseudoplatanus*)	7% Common maple (*Acer pseudoplatanus*)
Leaf chlorosis (proportion)	7% Common ash (*Fraxinus excelsior*)	30% Common ash (*Fraxinus excelsior*)	60% Common ash (*Fraxinus excelsior*)	40% European hornbeam (*Carpinus betulus)*	7% Common maple (*Acer pseudoplatanus*)

The research results show that open (permeable) and moderately dense (semi-permeable) windbreak belts are represented by both main and secondary tree species, while dense (impermeable) belts consist exclusively of main species. Semi-permeable windbreak belts exhibit the greatest species diversity, while permeable belts show the least. This is consistent with the theoretical principle that greater structural complexity contributes to higher biological diversity (Yahner, 1983; Peters & Nibbelink, 2011).

The widespread dieback of *Fraxinus* sp. represents the most serious current problem and significantly undermines the protective function of the belts. The detection of symptoms characteristic of *Hymenoscyphus fraxineus* is particularly concerning, as this disease is widely spread across Europe and no effective treatment exists at the stand level. Onchevski et al. (2022) established a direct correlation between the degree of degradation and reduced wind speed reduction efficiency, at 33% of felled trees in permeable belts, the protective function is practically compromised. In the medium term, the key challenge is the need for reconstruction of degraded areas through the introduction of adapted, disease-resistant, and climatically suitable tree species.

The underlying problems as inappropriate selection of tree species during the original afforestation (monocultural dominance of *Fraxinus*), insufficiently planned spatial arrangement of preparatory and supplementary rows, absence of systematic maintenance following the transitional period, and the lack of a long-term national strategy, stem from a shortage of experience and professional and institutional expertise during the transition period. The identified issues (unclear responsibilities between the state, local authorities, and private landowners, lack of monitoring, and illegal logging) point to the need for a comprehensive, integrated management concept for the windbreak belts of Ovche Pole (FAO, 2014; JICA, 2023).

A comparison with international experience shows that countries which have successfully restored and maintained shelterbelt systems, such as Ukraine, Kazakhstan, and China, share a common denominator: a clear national strategy with long-term funding, legal protection of forest belts, farmer engagement through agro-environment schemes, and systematic monitoring (Kulik and Vlasenko, 2024; Tkachuk et al., 2025). North Macedonia can draw valuable lessons from the JICA Eco-DRR project experience (JICA, 2023b), which demonstrated that international knowledge transfer, combined with local engagement, can yield tangible results within as little as five years.

CONCLUDING REMARKS

The agrotechnical and agroecological impact of windbreak belts in Ovce Pole represents an important factor for the sustainable development of agriculture and environmental protection. The results confirm their multiple functions, protection of soil against wind erosion, improvement of microclimatic conditions, enhancement of agricultural productivity, and contribution to biodiversity and carbon balance. These systems represent a form of natural infrastructure whose value can hardly be replaced by technical measures.

The conducted empirical analysis shows that a significant proportion of the windbreak belts in Ovce Pole are degraded, fragmented, or destroyed. The widespread decline of ash trees (*Fraxinus sp.*), with 33% of trees cut or dried out in the main permeable windbreak belts, was identified as the most urgent current problem. The high levels of leaf necrosis and chlorosis indicate that the systems are under intense physiological stress. The main causes include changes in land ownership structure following the transition period, lack of institutional protection, absence of strategic planning, and a low level of awareness regarding the importance of these systems.

The restoration, maintenance, and development of windbreak belts in Ovce Pole are necessary and strategically justified measures. Their integration into modern agroecological policies, with support from institutions, farmers, and the scientific community, will contribute to long-term land protection, increased productivity, improved resilience to climate change, and sustainable environmental management. Windbreak belts are not merely a forestry measure, but a complex agroecological system of crucial importance for the future of agriculture in the Ovce Pole region and more broadly across the lowland areas of the Republic of North Macedonia.

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АГРОЕКОЛОШКА СОСТОЈБА И ФУНКЦИОНАЛНОСТ НА ВЕТРОЗАШТИТНИТЕ ПОЈАСИ ВО ОВЧЕ ПОЛЕ

Јорданчо Димитриев[1,2*], Фиданка Трајкова[1], Љупчо Михајлов[1]

[1]Земјоделски факултет, Универзитет „Гоце Делчев", Штип, „Крсте Мисирков" 10-А, 2000 Штип, Република Северна Македонија

[2]Министерство за земјоделство, шумарство и водостопанство, Инспекторат за шумарство и ловство, Република Северна Македонија

**Контакт автор: jordanco.209148@student.ugd.edu.mk*

Резиме

Ветрозаштитните шумски појаси во Овчеполскиот Регион се формирани пред приближно 65 години со цел заштита на земјоделското земјиште, намалување на еолската ерозија и подобрување на локалната микроклима. Поради нивната старост, недоволното одржување, интензивирањето на земјоделството, антропогените влијанија и последиците од климатските промени, значителен дел од овие појаси бележи намалување на заштитните и еколошките функции. Целта на ова истражување е да се процени моменталната агроеколошка состојба, структура и функционалност на избрани ветрозаштитни појаси во Овчеполскиот Регион, со посебен осврт на подрачјето на Општина Свети Николе. Методологијата на истражувањето опфаќа преглед на релевантна литература, теренски набљудувања, GPS-геореференцирање, морфометриски мерења, дендролошка анализа на состојбата на вегетацијата. Оценетите индикатори вклучуваат континуитет на појасите, состав на видовите, удел на исечени и суви дрвја, појава на сушење, тревна покривка, изгазена вегетација и присуство на некроза и хлороза на листовите. Значителен дел од истражуваните појаси е деградиран, фрагментиран или погоден од незаконска сеча, природно стареење, сушен стрес (стрес од суша) и несоодветно управување. Резултатите од ова истражување покажуваат дека значителен дел од истражуваните појаси се деградирани, фрагментирани или под влијание на нелегални сечи, природно стареење, стрес од суша и несоодветно управување. Ова истражување ја потврдува важноста на ветрозаштитните појаси за стабилноста на агроекосистемот и ја нагласува потребата од системска обнова, засилена институционална заштита и долгорочно одржување.

Клучни зборови: *еолска ерозија, микроклима, агроекосистеми, заштита на почва, одржливо земјоделство.*